

**Final Technical Report for USGS Award G17AP00043**

**Tuning and Validating High-frequency Ground Motion Variability in the  
SDSU Broadband Method  
by**

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## Summary

We have validated the San Diego State University (SDSU) implemented on the Southern California Earthquake Center (SCEC) Broadband Platform (BBP) module, which combines deterministic (low-frequency) and stochastic (high-frequency) components, in terms of ground motion duration, intra-event variability, and peak spectral acceleration (PSA) against NGA-West2 GMPEs. Our results show significantly improved 50-realization PSA Goodness-of-Fit (GOF) to NGA-West2, by adjusting the shape and amplitude of the source-time function convolved with the high-frequency scattering functions in the SDSU BBP module. We find that the SDSU module produces median intra-event standard deviations of 0.6-0.75, slightly higher than those for NGA-West2.

We validated the durations associated with the SDSU module high-frequency (HF) synthetics, after refining the scattering parameters in the code. The current technique of estimating the goodness-of-fit (GOF) for durations on the SCEC BBP aligns synthetic and recorded time series to the time of the 5% energy and truncates the synthetic time series when the data record ends. We find that this technique can provide a biased GOF value when the data is truncated (i.e., due to too short of a recording window). We find that the synthetics should **not** be truncated to provide a fair comparison. We have eliminated data records that appear to be truncated and several bugs in the BBP GOF procedure associated with time interpolation and alignment fixed. 50-realization significant duration estimates from the updated SDSU module showed generally improved GOF for historical Western US (WUS) and Japanese events.

Earthquake ground motion records reveal frequency-dependent correlations, which has implication for seismic risk (Bayless and Abrahamson, 2018). The empirical inter-period correlations of the parameter epsilon using the Effective Amplitude Spectrum (EAS) computed from the Pacific Earthquake Engineering Research Center (PEER) NGA-West2 database shows that the ground motion at nearby frequencies are correlated. We have developed a post-processing method to incorporate such correlation into the current SDSU BBP module. Using our improved method, the results for 7 M5.0-7.2 WUS events show that the realistic inter-period correlations of EAS are well predicted in the SDSU module for a large number of realizations from a single event with unbiased GOF of the spectral accelerations in the presence of correlated synthetics.

Burks and Baker (2014) proposed a list of metrics that act as proxies for more complicated engineering measures, as a guidance for validation. One of these metrics were ratios of maximum (among all directions) spectral acceleration (SARotD100) to median RotD spectral acceleration (SARotD50). We show that the ratios for the BB synthetics for 5 WUS earthquakes vary between 1.2 and 1.35, increasing as a function of frequency. For periods less than 1 s (obtained from the scattering functions in BBtoolbox), the ratios agree very well between the data and synthetics.

The SDSU module including the modifications resulting from this research will be included in the next official code release from the SCEC BBP and can be obtained from there. Until this release, the code can be obtained upon request to kbolsen@sdsu.edu.

# Final Technical Report

## Introduction

It is the ultimate goal for ground motion modelers to deliver their results to engineers and see their work used in real applications, such as structural design. However, the synthetics need to be thoroughly validated before they can be applied. Burks and Baker (2014, BB14) presented a validation system for simulated ground motions, proposing a list of metrics that act as proxies for more complicated engineering measures. This list includes, among others, correlation of spectral acceleration across periods (shown by Bayless and Abrahamson (2018) to have important implications for the seismic risk) and ratio of maximum-to-median spectral acceleration. The result of applying these metrics to several of the computational modules on the SCEC BBP revealed poor match at higher frequencies. This is not too surprising, as the main focus on the modules (in the SCEC validation exercise and beyond) has been extensive calibration of median SAs by NGA-West1 GMPEs and strong motion data, aiming at generating methods capable of predicting accurate pseudo-spectral accelerations in general.

The SDSU method is one of the broadband ground motion generator modules of the SCEC BBP. The method, merging low-frequency deterministic signals with high-frequency scattering functions (Olsen and Takedatsu, 2015), participated in and passed the SCEC Broadband Platform validation exercise. Here, we look beyond the previous validation of median SAs and examine the SDSU module's performance for additional metrics. As the SCEC validation used the NGA-West1 relations, we here test the SDSU BBP synthetics against median NGA-West2 horizontal PSA levels and propose code changes to improve the comparisons. We also validate signal duration, distance-dependent intra-event standard deviation, and maximum-to-median PSA levels for Western United States and Japanese historical earthquakes.

## The SDSU Broadband Platform (BBtoolbox)

The Southern California Earthquake Center (SCEC) has completed Phase 1 of its Broadband Platform (BBP) ground motion simulation results, evaluating the potential applications for engineering of the resulting 0.01-10 s Pseudo-Spectral Accelerations (PSAs) generated by 5 different methods. The exercise included part A, where the methods were evaluated based on the bias of simulation results to observations for 12 well-recorded historical earthquakes: 7 in western U.S., 2 in Japan, and 3 in eastern US/Canada. In addition, part B evaluated simulation results for  $M_w5.5$ ,  $M_w6.2$  and  $M_w6.6$  scenarios at 20 km and 50 km from the fault. The methods were assessed based on the bias of the median PSA for the 12 events in part A, and on a specified acceptance criterion compared to NGA-West Ground Motion Prediction Equations (GMPEs) in part B. The results were evaluated by the bias of mean PSA from simulations using 1D velocity models with  $V_s^{\min}=863$  m/s with respect to recorded data corrected for site effects.

One of the 5 methods evaluated was the Broadband Synthetics Generator Module BBtoolbox V1.5, a hybrid method combining deterministic low-frequency (LF) synthetics with high-frequency (HF) scatterograms (Olsen and Takedatsu, 2015, and earlier versions discussed by Mai et al., 2010, and Mena et al., 2010). The LFs may be computed using deterministic or dynamic descriptions in 1D or 3D media. The HF scatterograms are generated for each component of motion based on the theory for multiple scattering by Zeng et al. (1991, 1993). The scatterograms are based on user-specified site-scattering parameters and are partly based on the site-specific velocity structure. The seismic scattering wave energy is realized to appear after the direct P wave arrival time, which is found from 3D ray tracing (Hole, 1992). Finally, the scatterograms are convolved with an appropriate source-time function. It is assumed that the scattering operators and moment release originate throughout the fault, but starts at the hypocenter. The hybrid broadband seismograms are calculated in the frequency domain using a simultaneous amplitude and phase matching algorithm (Mai and Beroza, 2003). In the validation exercise, the LFs are generated using 50 source realizations from the kinematic source generator module by Graves and Pitarka (2015, GP15).

BBtoolbox V1.5 was validated on the BBP for the SCEC validation Phase 1. Figure 1 shows bias of PSA for an ensemble of 50 realizations for the 7 western U.S. and 2 Japan events (Part A). In general, the fits are good. The fits are generally better for shorter periods ( $<1$ s), as there is some tendency to overpredict for the longer periods ( $>1$ s) generated by 1D Green's functions and the GP15 source generator.

The performance of the SDSU module for part B (NGA-West1 GMPEs) of the validation is shown in Figure 2 for northern California velocity structure. Here, PSAs (0.01-10s) for  $M_w5.5$ ,  $M_w6.2$ , and  $M_w6.6$  scenarios are compared for simulations and leading GMPEs (see Goulet et al., 2015, for definition of the acceptance criteria). The mean PSAs from the simulations obtained by the SDSU module show very good agreement with the GMPEs and fall within the applicable acceptance criteria for all scenario periods.

## **Period-to-Period Correlation**

The SDSU module V1.5 (Olsen and Takedatsu, 2015) does not incorporate the realistic inter-frequency correlations of FAS into the simulations. Figure 3 (left) shows the resulting inter-frequency correlation coefficients of 50 realizations for 5 of the SCEC validation events: Landers ( $M7.22$ , 1992), Loma Prieta ( $M6.94$ , 1989), Northridge ( $M6.73$ , 1994), Whittier ( $M5.89$ , 1987), Chino Hills ( $M5.39$ , 2008) from the current SDSU broadband synthetics compared with the empirical results, revealing almost no correlations between frequencies for the synthetics, in particular at higher frequencies ( $>1$  Hz).

While the past validations have used PSA, we will turn to the Fourier Amplitude Spectrum (FAS), which represents a more flexible domain that is gaining traction in recent validations. For example, FAS, unlike PSA, depicts the spectral amplitudes at individual

frequencies, independent of the adjacent frequencies. The Effective Amplitude Spectrum (EAS) of the Fourier Amplitude Spectrum (FAS) are used in our study, which is the geometric mean of the two horizontal FAS components. We define the within-event residual as the misfit between an individual EAS observation at a station and the earthquake-specific median prediction. We also use epsilon ( $\epsilon$ ), the within-event residual normalized by its respective standard deviation. Due to the normalization, epsilon is normally distributed.

To improve the FAS correlations in the SDSU module, we have developed a post-processing method to implement inter-frequency correlations into the SDSU broadband synthetics. Making use of the empirical covariance matrix  $\Sigma$  (real, symmetric and positive definite) for the period-to-period correlation of FAS regressed from the NGA-West2 database by Bayless and Abrahamson, we first apply a Cholesky decomposition of  $\Sigma$ ,

$$\Sigma = KK^T,$$

where  $K$  is a lower triangular matrix. An uncorrelated normal random variable  $R$  is then generated with zero mean and a constant standard deviation,  $\sigma = 0.5$ , for each realization. The random variable is multiplied by  $K$  to get a correlated normal random variable  $S$  with zero mean and covariance equals  $\sigma^2\Sigma$

$$S = KR.$$

Figure 4 shows an example of the uncorrelated normal random variable  $R$ , the correlated normal random variable  $S$ , and the exponential of  $S$ , the original uncorrelated Fourier amplitude of velocities and the correlated Fourier amplitude of velocities after multiplying by the exponential of  $S$ . Next, we multiply the exponential of the correlated normal random variable with the original FAS, generating ground motion time series with realistic inter-frequency correlations by an inverse Fourier transform of the correlated FAS. Figure 5 shows an example pair of epsilon at 2.0 Hz and 2.5 Hz before and after the implementation. Epsilon is almost uncorrelated in the original SDSU synthetics with correlation coefficient equal to only 0.05, but shows realistic correlation in the improved SDSU synthetics with a correlation coefficient of 0.67.

We validate the method by computing broadband ground motions including inter-frequency correlations for 7 validation events: Landers (M7.22, 1992), Loma Prieta (M6.94, 1989), Northridge (M6.73, 1994), North Palm Springs (M6.12, 1986), Whittier (M5.89, 1987), Chino Hills (M5.39, 2008) and Alum Rock (M5.45, 2007). Figure 3 (right) shows the resulting inter-frequency correlation coefficients of 50 realizations for the 5 events from the improved SDSU broadband synthetics with the correlations implemented compared with the empirical results. Using our method, the period-to-period correlations are well simulated for both low-frequency and high-frequency signals.

Figure 6 shows the comparison of the logarithm misfit between the median observation and the median prediction for the current and improved SDSU synthetics. The

misfits are similar before and after the implementation, which shows that the median spectral accelerations are not significantly affected by the implementation of correlations. In addition, our method generates velocity and acceleration time series and FAS that are very similar to the original results from current SDSU module. For example, Figure 7 shows the north-south component of accelerations at station 8001-CLS, as well as FAS before and after implementing the inter-frequency correlations at station CLS for the Loma Prieta event simulations.

For some events and periods, the results after we apply the correlation method still underpredict that of the empirical relations (see Figure 6). This is presumably due to the smoothing introduced by the EAS using the Konno & Ohmachi (1998) operator, that can cause slight decorrelation applied to the random variable  $S$ . To compensate for this smoothing, it is possible to apply an ‘overshoot model’ to the uncorrelated random variable  $R$  and generate the correlated random variable  $S$  with covariance matrix  $\Sigma_{os}$ , where  $\Sigma_{os}$  provides a larger amount of correlation.

$$\Sigma_{os} = \frac{1}{2}(\Sigma + \Sigma^+)$$

where  $\Sigma^+$  provides the additional amount of correlation. In Figure 8, we show the effect of using  $\Sigma^+ = \Sigma_{1.8}^{\frac{1}{1.8}}$  for the Loma Prieta event. It is clear that the ‘overshoot’ model may be able to provide a better fit with the empirical correlations for some periods.

It should be noted that the implementation of the correlation was carried out using a modified version of SDSU, merging the LFs and HFs in the time domain using a matched filter techniques, similar to that used by Graves and Pitarka (2010, 2015). The reason is that we noticed some artifacts in the correlation results using the frequency-domain merging technique, that were not present using the time-domain merging method. However, the details of the proposed method for implementing the correlation is independent of the merging method if applied to the HF only, which is the main goal of the project.

## **Validation of BBtoolbox V1.5 PSA against NGA-west2**

Part B of the SCEC BBP Validation exercise Phase 1 used the NGA-west1 GMPEs, with which BBtoolbox V1.5 compared very well (see Figure 2). However, the more recent NGA-west2 GMPEs are expected to be more accurate, and it is imperative to compare the broadband synthetics to the updated relations. Figure 9 shows a comparison of the median PSA for NGA-West 1 and NGA-West 2 for M5.5 and M6.6 strike-slip events, with the tolerance used in the SCEC Validation. The primary difference is lower NGA-West 2 versus 1 PSA values for 0.15-0.4 s, with smaller deviations at other periods (such as slightly larger NGA-West 2 versus 1 values at 0.03-0.1s).

We have made several improvements to fit the NGA-West2 relations by adjusting the shape and amplitude of the source-time function convolved with the high-frequency

scattering functions in the SDSU BBP module (Figure 10). The shape of the source time function (stf) is defined as

$$\text{stf}(t) = t^{n_1} / [1 + (t/t_1)^n],$$

where  $t$  is time and  $t_1$  is the rise time. In BBtoolbox V1.5,  $n = 2.0$ ,  $n_1 = 0.5$ . After careful comparison with between BBSynthetics and NGA-West2 results, we implemented the following parameters, differentiating between Western North America (WNA) and Japanese events:

*WNA events & if  $M_w < 6.2$ :*  $n = 2.75$  and  $n_1 = 0.6$ .

*Japanese events:*  $n = 2.75$  and  $n_1 = 0.5$ .

Using these region and magnitude-dependent parameters, we obtained significantly better fits to NGA-West2 PSA measured by the 50-realization bias. The improvements were obtained throughout Part A (Western and Japanese events) and Part B (GMPE comparisons). Figure 11 shows bias plots for 8 events (Northridge, Loma Prieta, Chino Hills, Landers, Whittier, North Palm Springs, Tottori, and Niigata). The changes in the bias of PSA from the refinement of the STF is small, and generally improving the bias (particular for periods between 0.03s and 0.3s). The largest improvements are obtained for North Palm Springs, Tottori and Niigata.

## Validation of Duration

The median levels of PSA are widely used by engineers for design, and was a natural first choice of metric in the SCEC BBP validation exercise. The PSA metric includes contributions from both amplitude and duration. However, a separation of the amplitude and duration components of PSA is desirable for a more targeted design analysis (i.e., when long durations are expected, such as sites in the directivity cone of a large strike-slip event). Thus, an important task was to validate the (HF) durations associated with the SDSU module synthetics.

We have selected the duration 5% and 95% of the energy in the seismic motion ( $D_{5-95\%}$ ) as the metric to validate, and our findings include the following. The current technique of estimating the GOF for durations on the SCEC BBP aligns synthetic and recorded time series to the time of the 5% energy and truncates the synthetic time series when the data record ends. However, we find that this technique can provide a biased GOF value when the data is truncated (i.e., due to too short of a recording window, see, e.g., Figure 12). We find that the synthetics should **not** be truncated to provide a fair comparison, which is how we have conducted our validation. In addition, to avoid bias, we have eliminated data records that appear to be truncated, and conducted the analysis on the HF component only, as the LFs are generated by a different method (and 1D Green's Functions). We detected several bugs in the BBP GOF procedure associated with time interpolation and alignment, and Fabio Silva of SCEC has fixed the issues after we alerted

him. Given that the recorded time series on the BBP include sites effects, but the synthetics do not, we computed the durations with and without correction for the simple frequency-dependent site amplification factors; however, the site correction did not change the results significantly.

Figure 13 (left) shows  $D_{5-95\%}$  durations for Northridge, Loma Prieta, Chino Hills, Landers, Whittier, North Palm Springs, Tottori, and Niigata, for the SDSU module V1.5, illustrating the general trend of too large durations as well as their standard deviations for the synthetics associated with all events.

In order to improve the fit between synthetic and observed durations (i.e., generally decrease the durations of the synthetics), we adjusted the scattering functions to better reproduce the envelope of observed accelerograms between the P and S arrivals (P-S and S-P scattering coefficient adjusted to 0.11, and the shape of the envelope from the P to the S arrival). We have also incorporated the changes of the source time function leading to the improved fit for the NGA-West2 results in our updated version of the SDSU BBP module. This new version of the SDSU module was run on the BBP with 50 realizations for all events. The bias was computed for a subset of stations where visual inspection suggested no truncation had occurred. Figure 12 (right) shows  $D_{5-95\%}$  durations for the 8 events for the updated SDSU module, illustrating the general trend of decreasing the durations and their standard deviations for all events. Most events show durations with improved fit to data.

## **Validation of SARotD100/SARotD50 Ratios**

The list of proxy metrics proposed by BB14 includes the ratio of orientation-independent maximum-to-median spectral acceleration, SARotD100/SARotD50. If SARotD100 is approximately equal to SARotD50, then the structural response is about the same in all orientations. If SARotD100 is much larger than SARotD50, then the structural response is polarized in one orientation. Figure 13 (left) shows the SARotD100/SARotD50 ratios calculated from the BB scenarios Chino Hills, Loma Prieta, Landers, Whittier, and Northridge as well as the seismic data recorded for these events. Ratios for both data and synthetics (2 realizations) are calculated from the ~40 stations used in the SCEC validation exercise. The results for both data and synthetics describe an increasing trend from ~1.2 at 0.1 s to ~1.3 at 10 s. This is in agreement with the ratios calculated from a large database of strong motion data by Shahi and Baker (2013, see Figure 13, right). The higher resolution of the Shahi and Baker (2013) also identifies a nearly constant level between periods of 0.5 and 2 s.

Withers et al. (2016) showed that the scattering and path effects from both the 3D background model and small-scale heterogeneities appears to be the controlling factors producing a good fit between the simulations and data for deterministic  $M_w 6.7$  blind thrust scenario simulations (Fig. 13, right). While the BB synthetics are not calculated using 3D velocity structure, they do include the HF effects of multiple S-S, S-P and P-S back scattering from the scattering operators in BBtoolbox. The ratios for the BB synthetics



vary between 1.2 and 1.35, increasing as a function of frequency. For periods less than 1 s (obtained from the scattering functions in BBtoolbox), the ratios agree very well between the data and synthetics. For the longest periods ( $> \sim 1$  s), obtained by deterministic 1D synthetics and kinematic source descriptions from the Graves-Pitarka rupture generator, the ratios for the synthetics are slightly larger than those from data. This result suggests that the SDSU BBP method synthetics produces high-frequency synthetics with RotD100/RotD50 ratios in very good agreement with data, but that the long-period synthetics generate slightly too large maximum amplitudes, possibly caused by excessive directivity effects.

### **Intra-event ground motion variability**

We tested the intra-event standard deviations for selected events with the SDSU module. Fig. 14 shows a comparison of intra-event standard deviations from simulations and GMPEs for 50 realizations of the Northridge and Loma Prieta events. We find that the SDSU module produces median 50-realization intra-event standard deviations between 0.6 and 0.75, slightly larger than that for the NGA-West2 GMPEs (BSSA14 and ASK14,  $\sim 0.54$  -  $0.58$ ), for both periods of 0.15 s and 0.3 s. The larger values for the synthetics is likely caused by the random variation used for the HF signal, which is easily scaled to the level observed.

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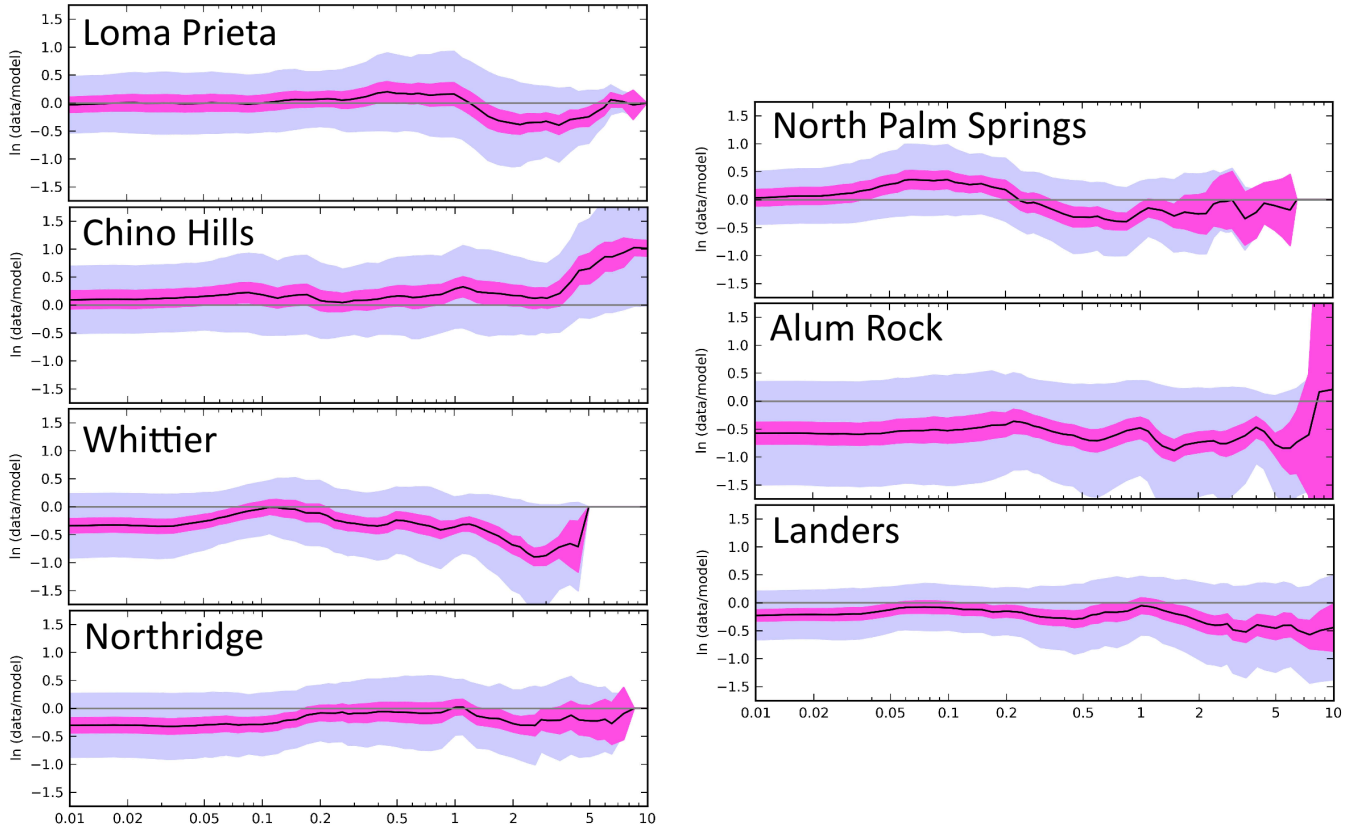
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### **Bibliography of Publications Resulting from the Work Performed Under the Award**

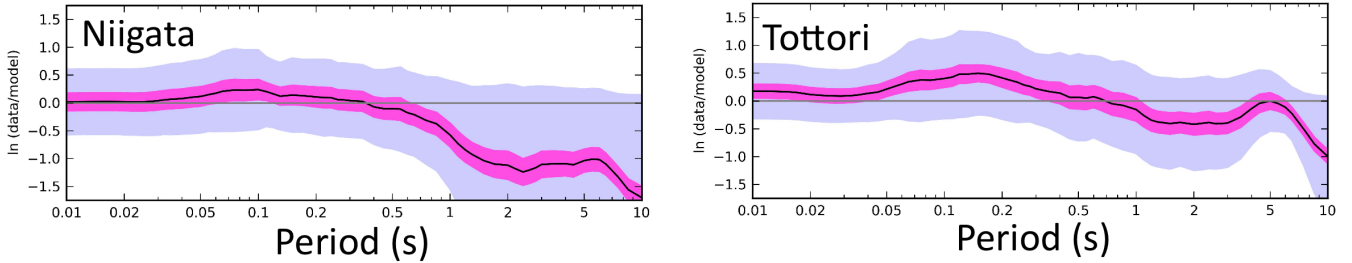
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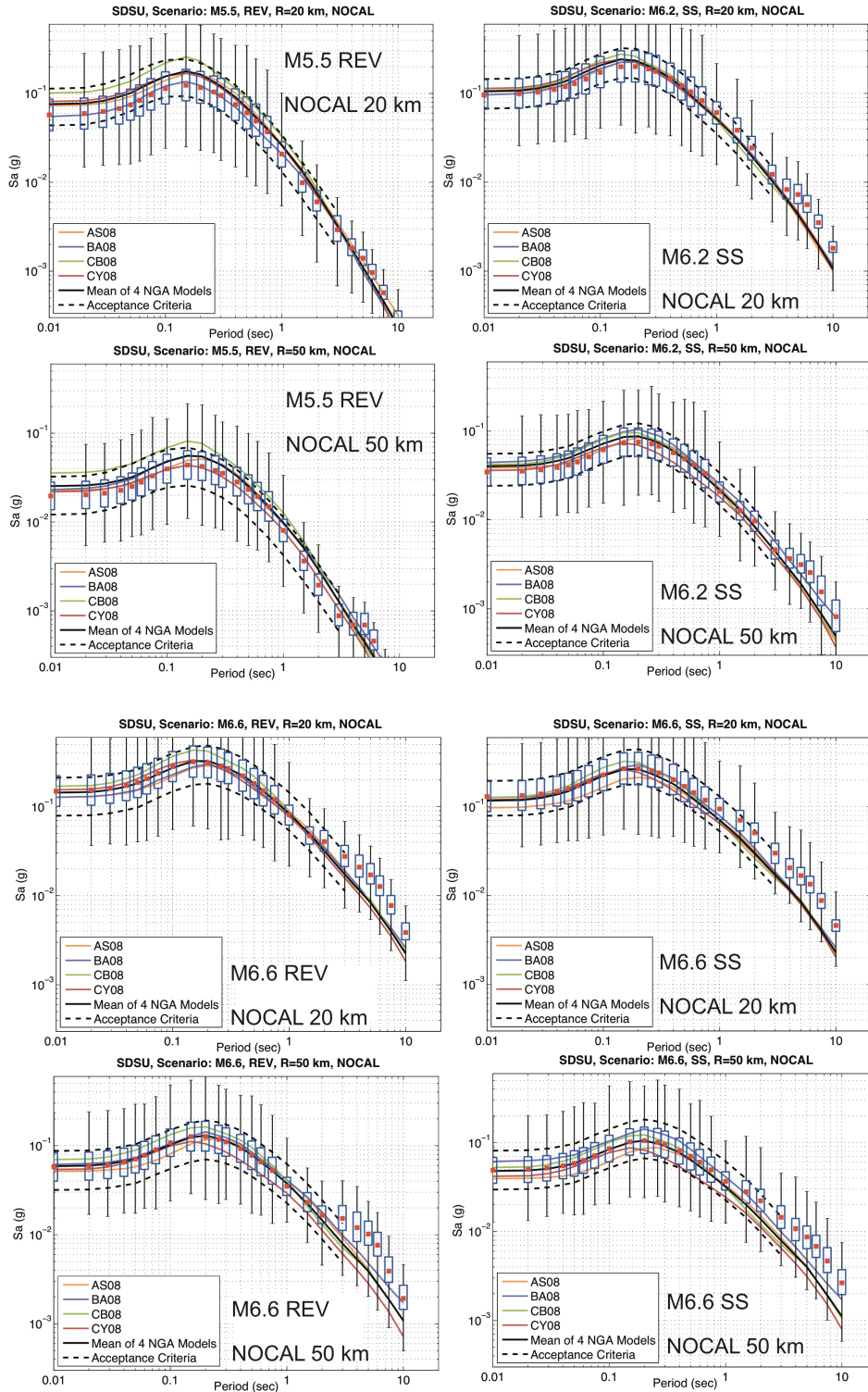
## Western U.S. Events



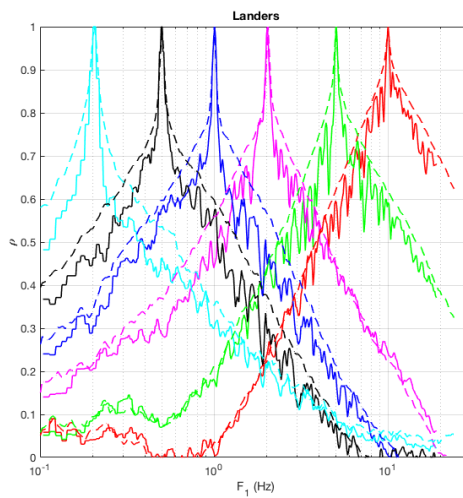
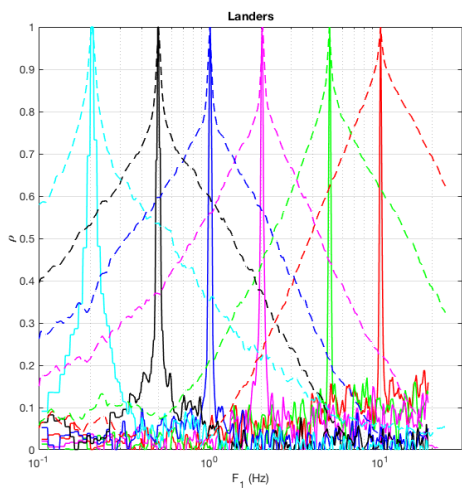
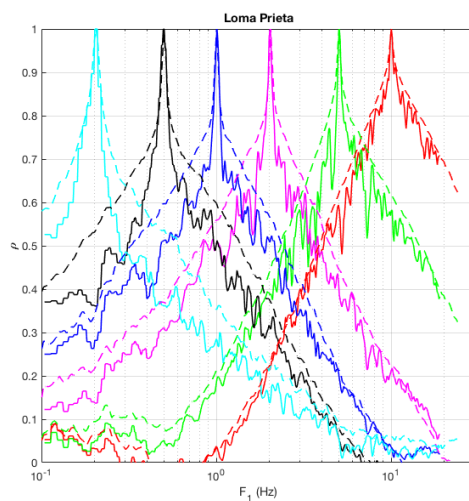
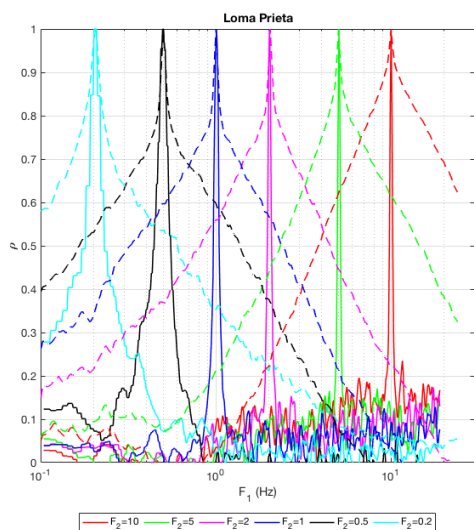
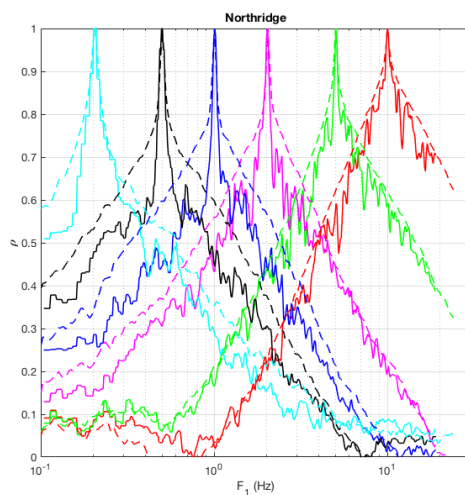
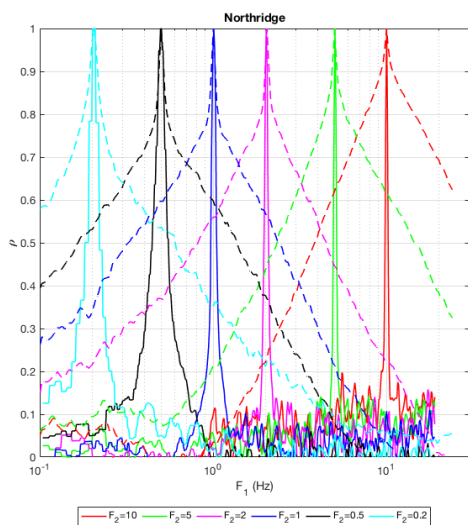
## Japan Events

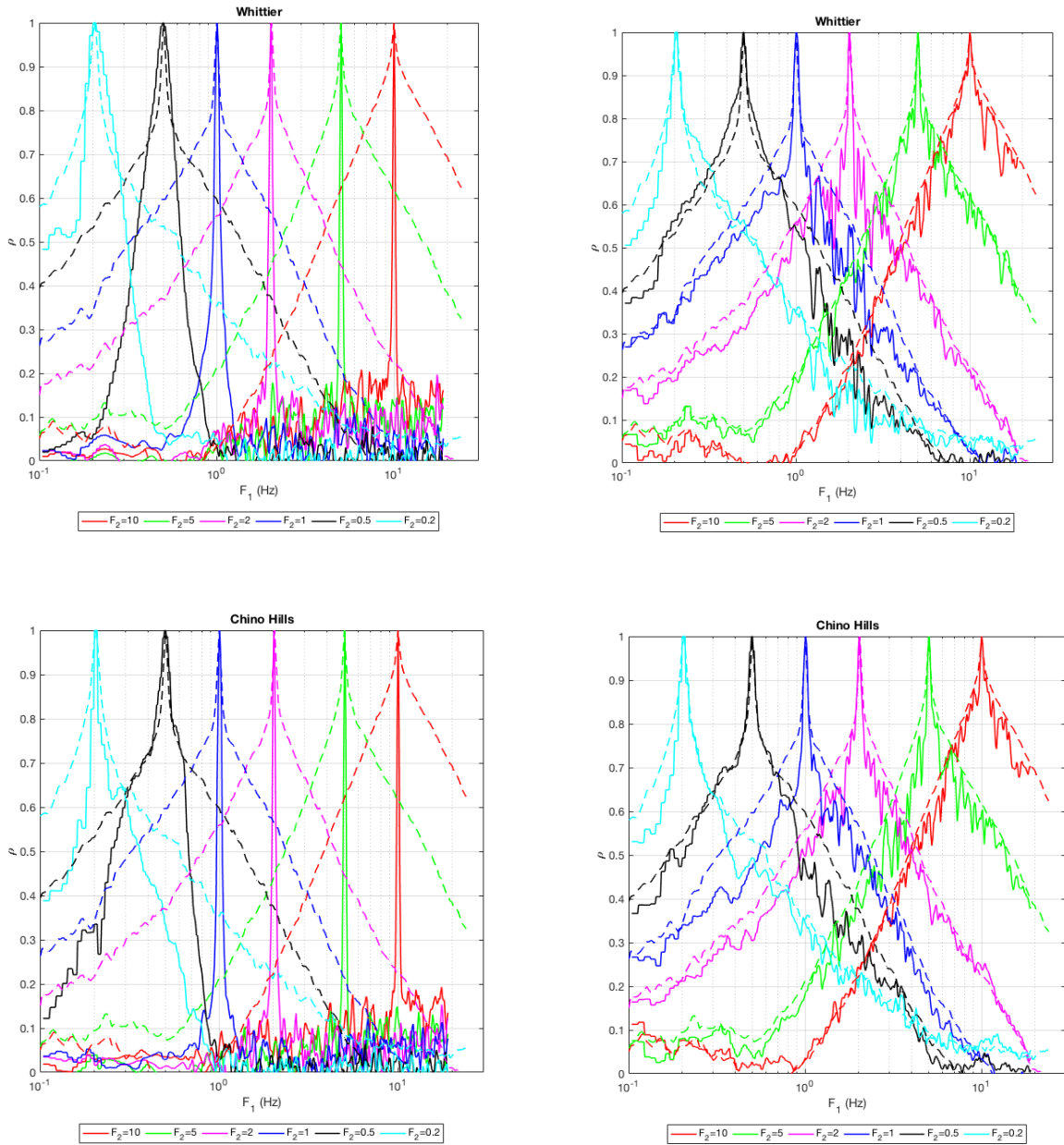


**Figure 1.** Combined (50 realization) PSA bias ( $\ln[\text{data}/\text{model}]$ ) for the 7 western US and 2 Japan events. Thick line depicts the median, purple shading shows the 95% confidence interval, and light blue shading is for the standard deviation. The large overprediction for Alum Rock for most periods is likely due to a large negative event term (average data residuals), supported by similar overprediction by leading GMPEs.

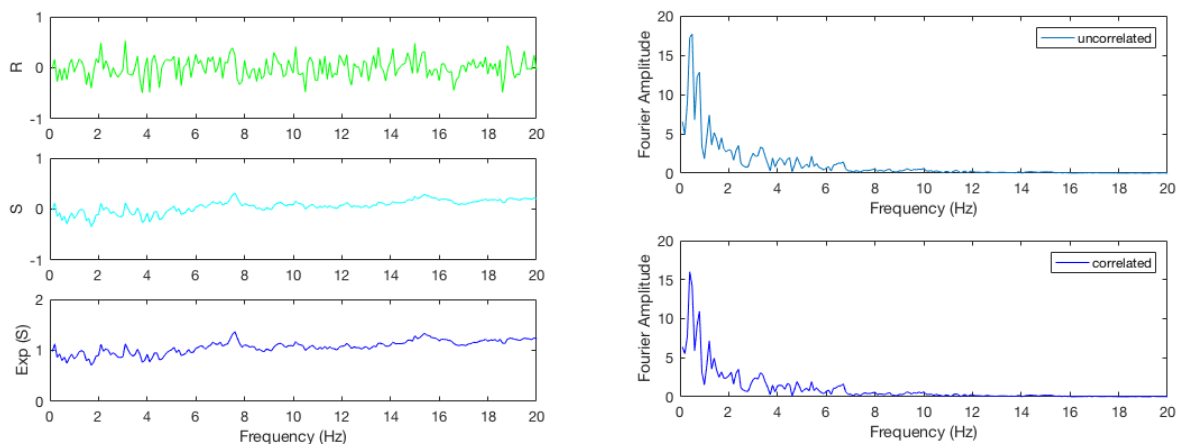


**Figure 2.** Part B of the validation comparing PSAs for 50-realization ensemble synthetics against leading GMPEs for  $M_w$  5.5, 6.2, and 6.6 scenarios. AS08, Abrahamson and Silva, 2008; BA08, Boore and Atkinson, 2008; CB08, Campbell and Bozorgnia, 2008; and CY08, Chiou and Youngs, 2008. The plots show the mean (square) and standard deviation (box), while error bars show extrema for all realizations.

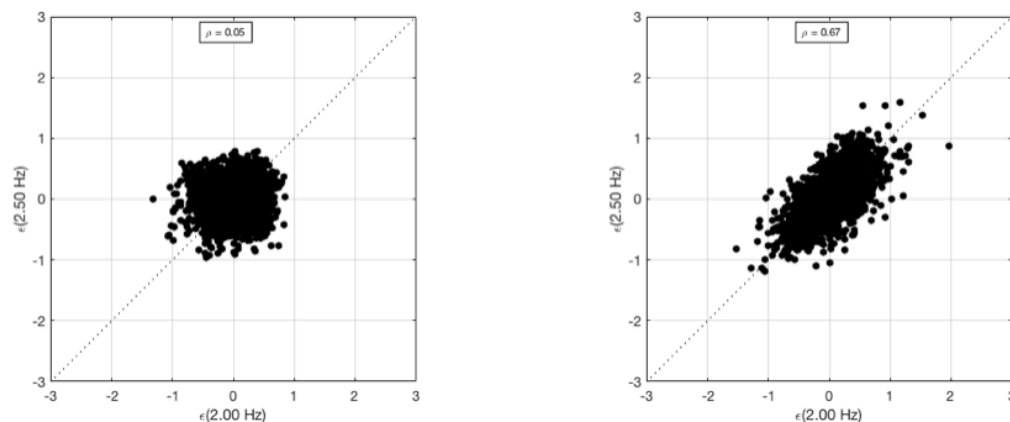




**Figure 3.** The inter-frequency correlation coefficients of epsilon at reference frequencies 0.2Hz, 0.5Hz, 1Hz, 2Hz, 5Hz and 10Hz from the current SDSU module of 50 realizations for Loma Prieta, Northridge, Chino Hills, Whittier, and Landers (solid lines) and the empirical correlation coefficients (dashed lines). (left) plots synthetic correlations before and (right) after applying the proposed method for including correlation.

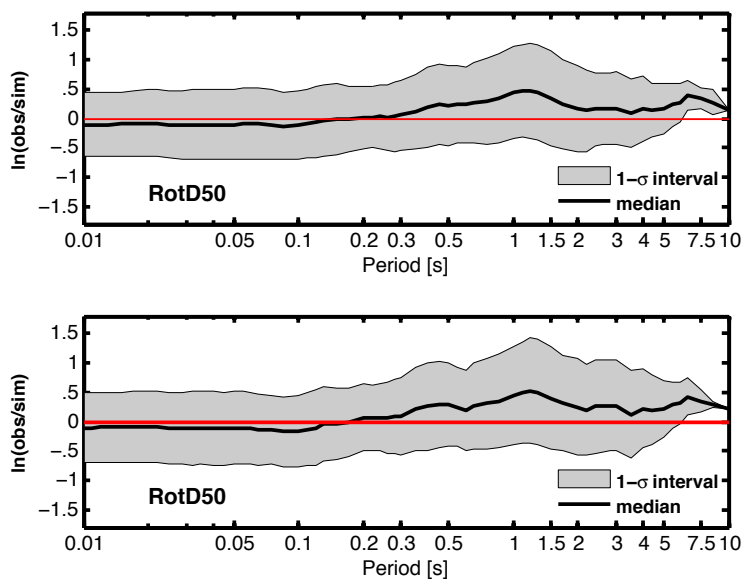


**Figure 4.** (left) Illustration of the generated uncorrelated normal random variable  $R$  (top), correlated normal random variable  $S$  (middle) and the exponential of  $S$  (bottom). (right) Example of the original uncorrelated Fourier amplitude of velocities (top) and the correlated Fourier amplitude of velocities after multiplying by the exponential of  $S$  (bottom).

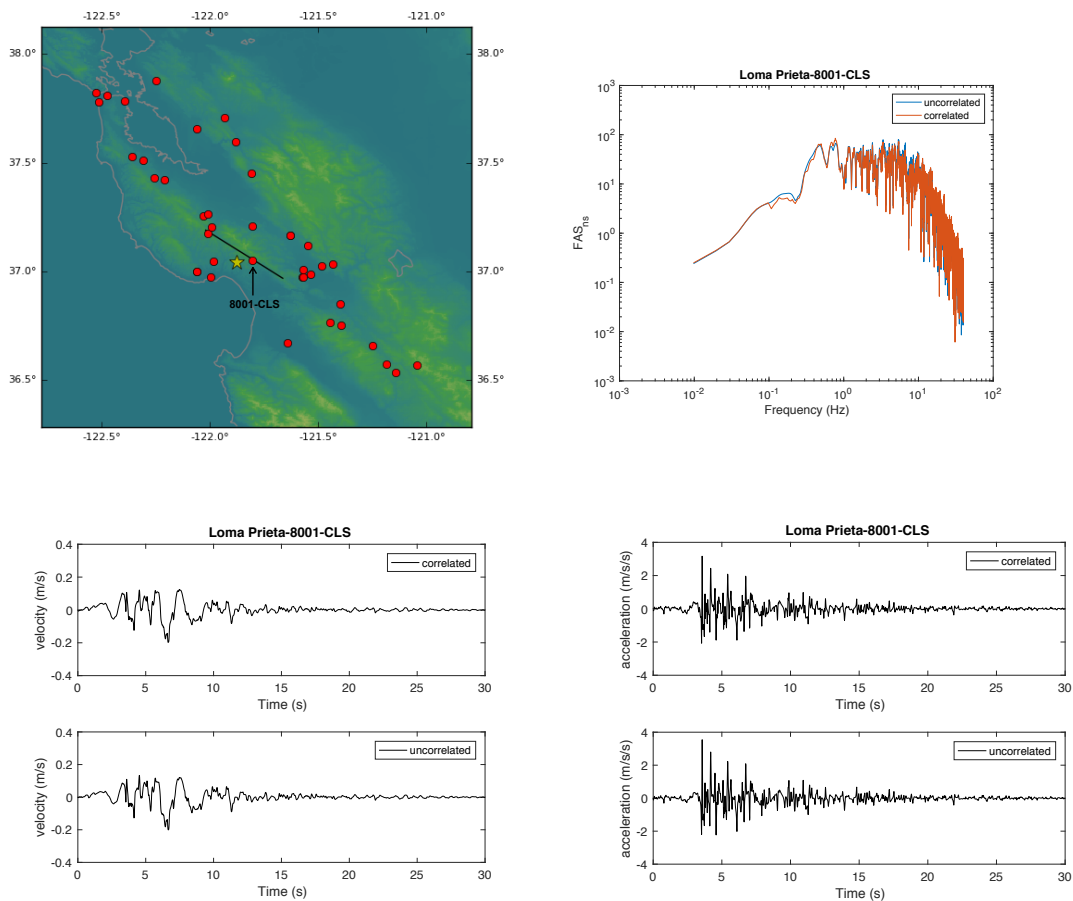


**Figure 5.** Correlation of an example epsilon pair at 2.0 Hz and 2.5 Hz before (left) and after (right) the implementation.

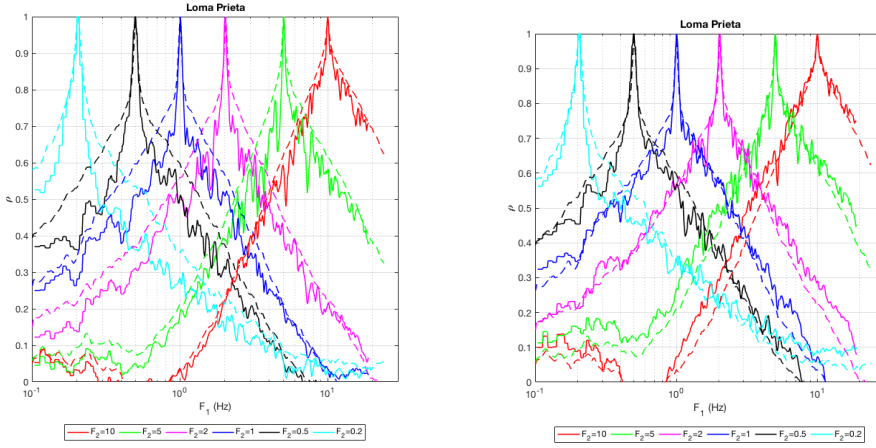




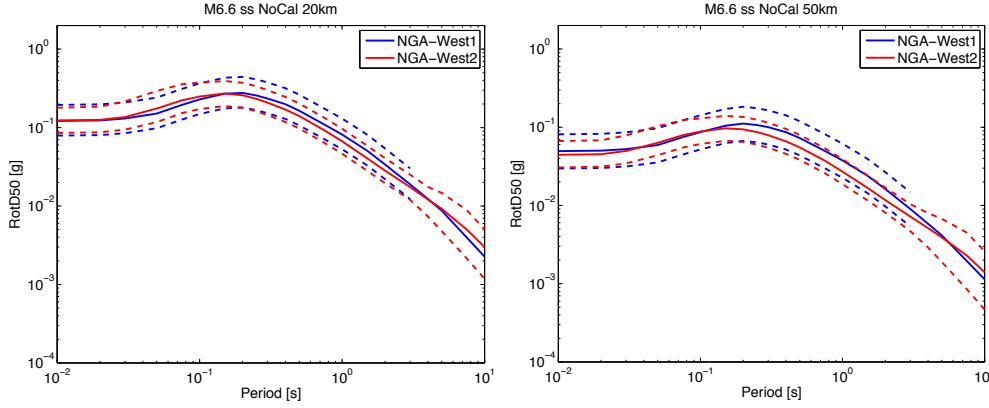
**Figure 6.** The logarithm misfit between the median observation of 50 realizations and the median prediction for the current (top) and improved (bottom) SDSU synthetics for Loma Prieta event.



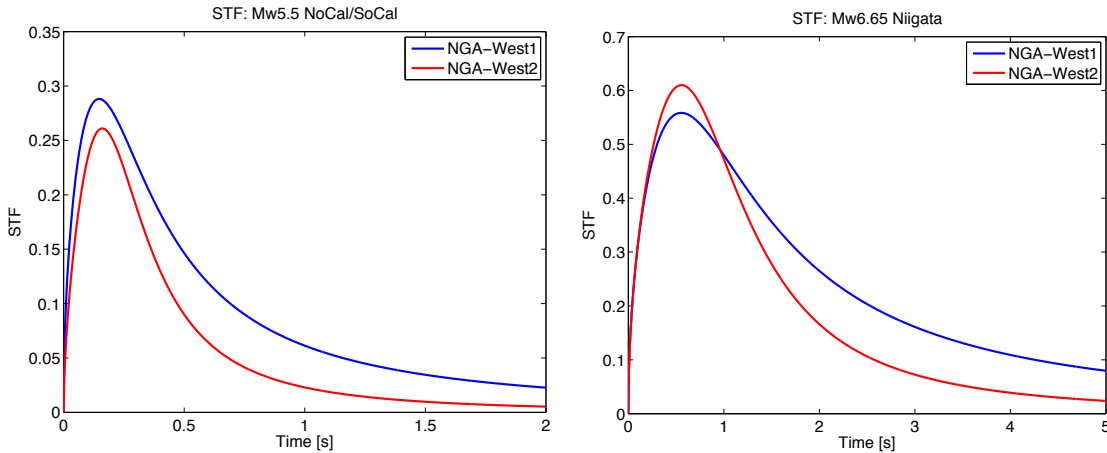
**Figure 7.** Examples of the north-south component of accelerations for one realization at station 8001-



**Figure 8.** The inter-frequency correlation coefficients of epsilon at reference frequencies 0.2 Hz, 0.5 Hz, 1 Hz, 2 Hz, 5 Hz and 10 Hz from the improved SDSU module of 50 realizations for the Loma Prieta event. (left) without and (right) with the overshoot correlation model implemented. Solid lines depict synthetics and dashed lines depict the empirical correlation coefficients.

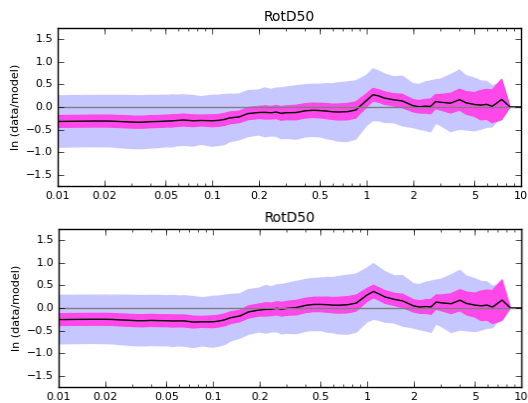


**Figure 9.** Average NGA-West1 and NGA-West2 GMPE median (solid) and tolerances (dashed) from the SCEC validation exercise.

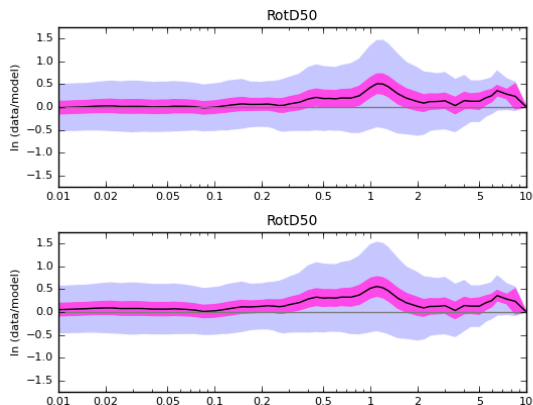


**Figure 10.** Source-time function used to convolve with the HF scattering functions for the NGA-West1

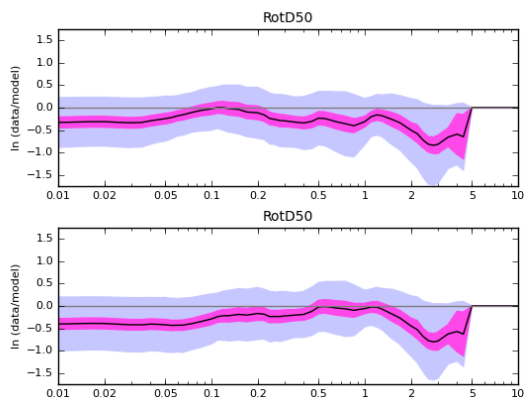
Combined GOF Plot for NR  
50 Realizations  
SDSU Method



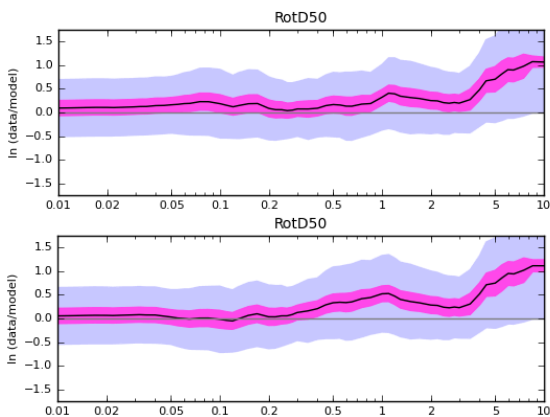
Combined GOF Plot for LOMAP  
50 Realizations  
SDSU Method



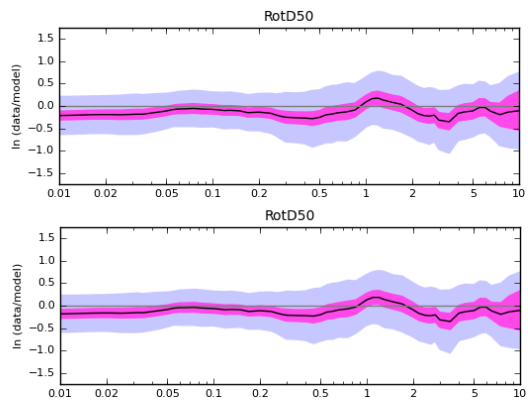
Combined GOF Plot for WHITTIER  
50 Realizations  
SDSU Method



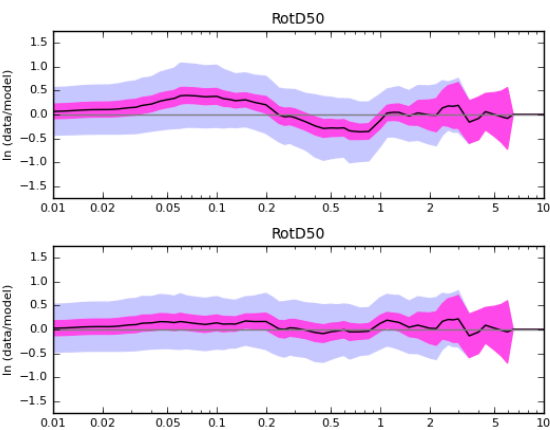
Combined GOF Plot for CHINOH  
50 Realizations  
SDSU Method

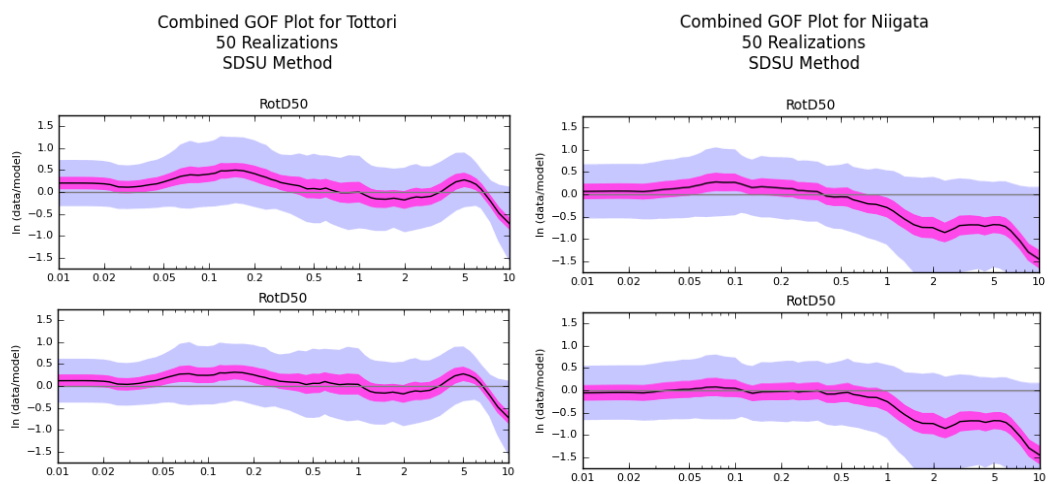


Combined GOF Plot for Landers  
50 Realizations  
SDSU Method

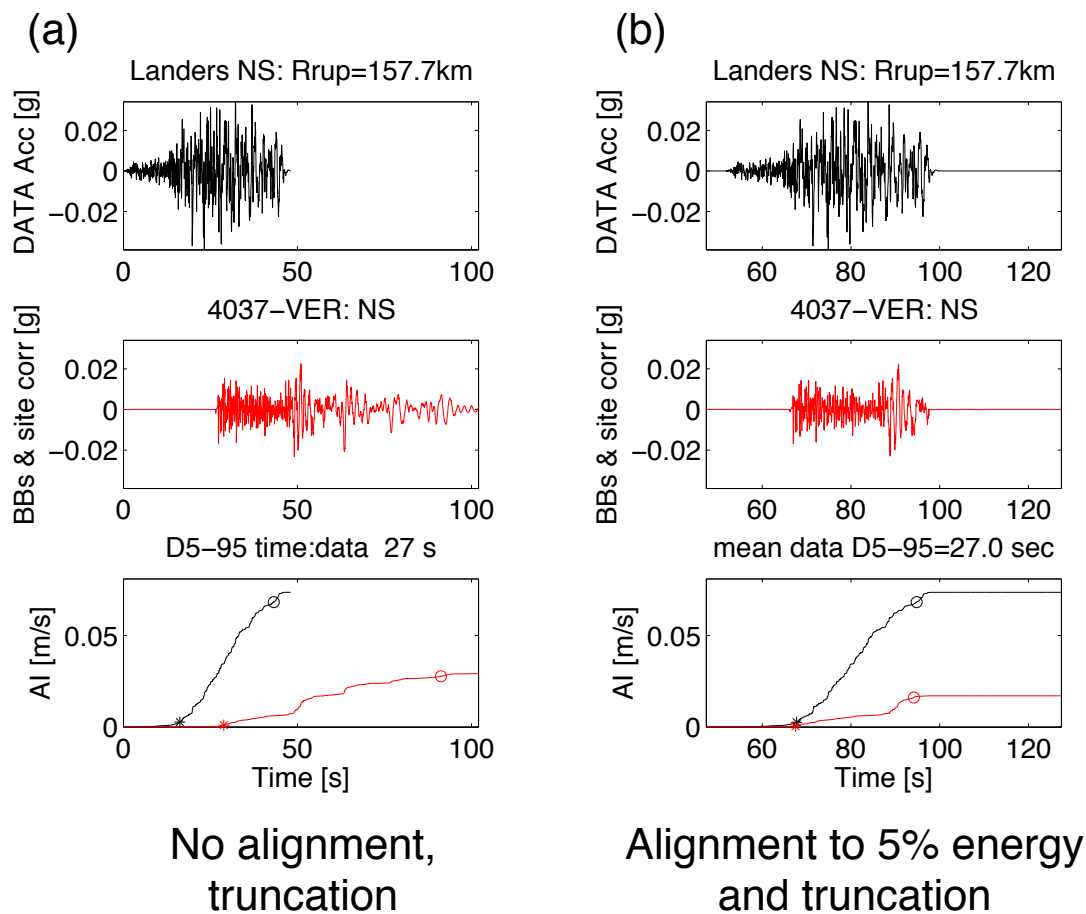


Combined GOF Plot for NORTHPS  
50 Realizations  
SDSU Method

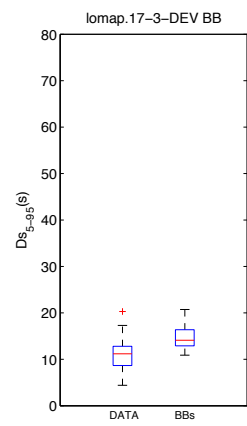
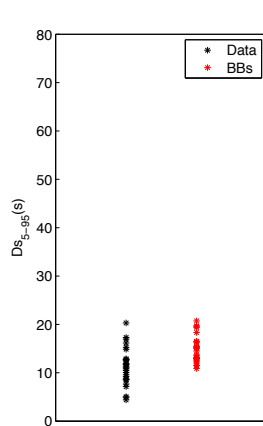
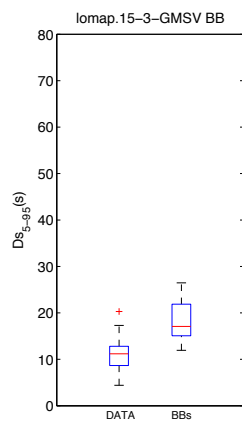
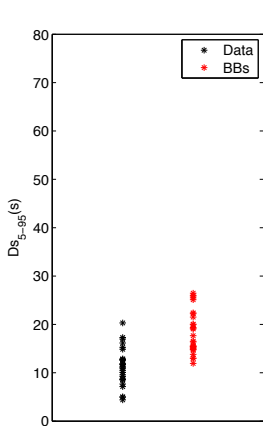
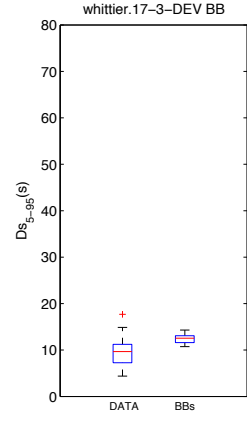
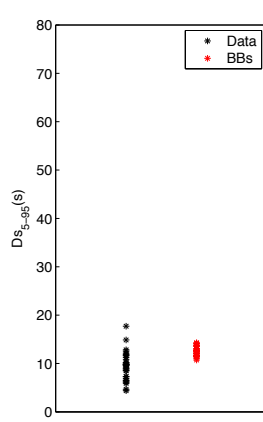
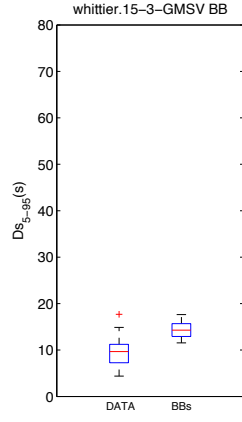
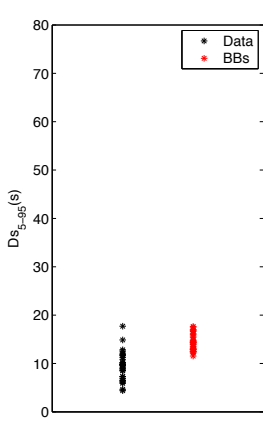
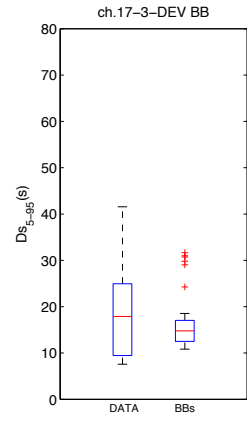
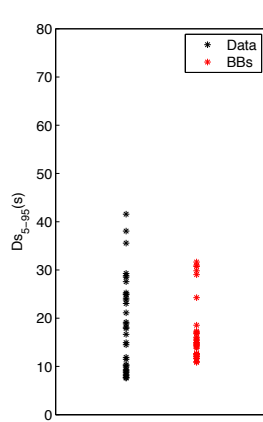
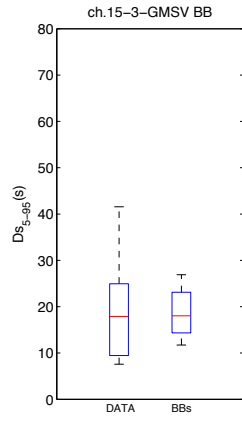
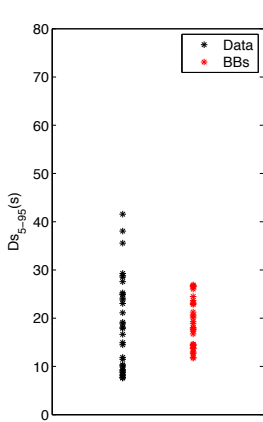


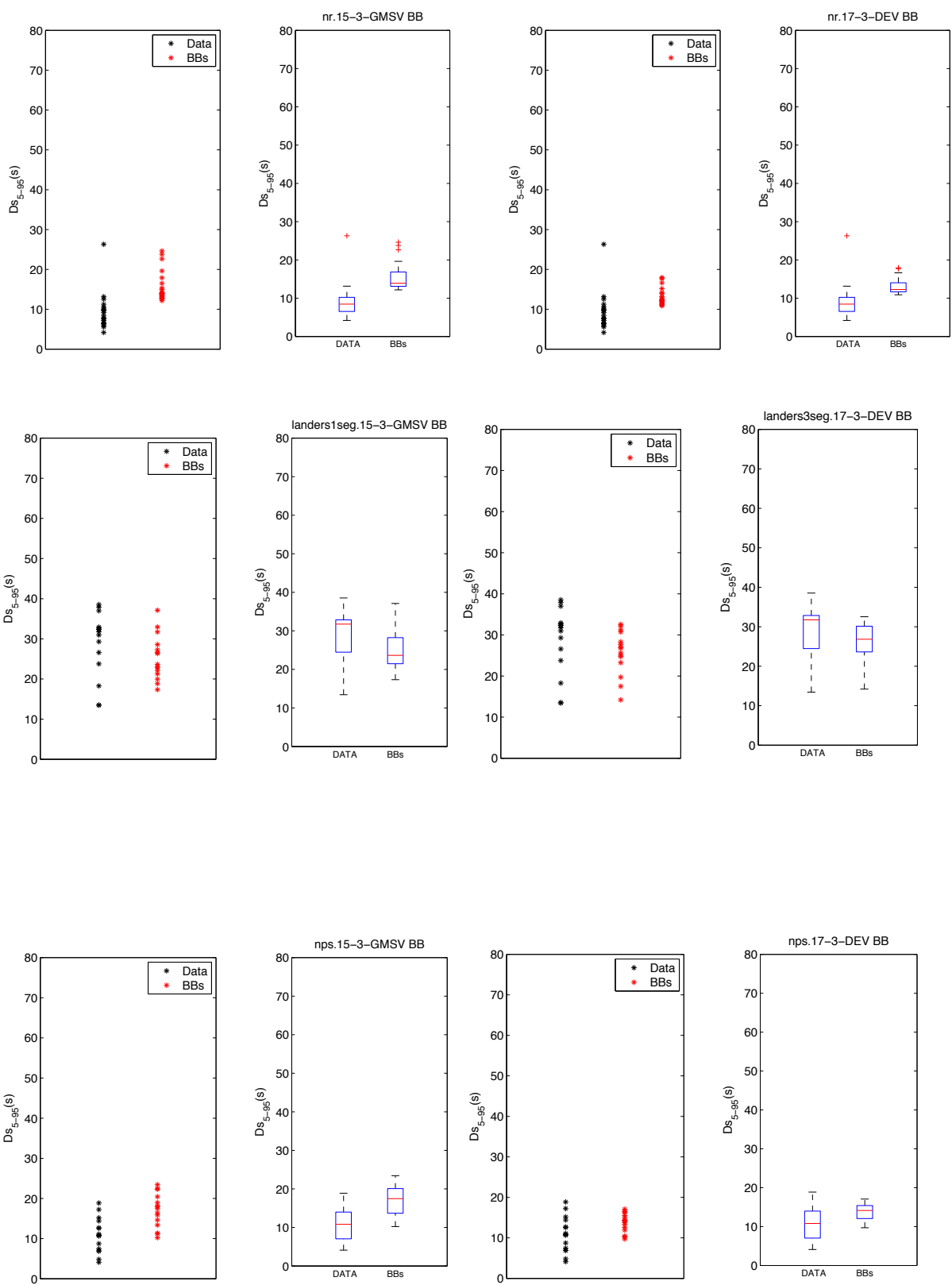


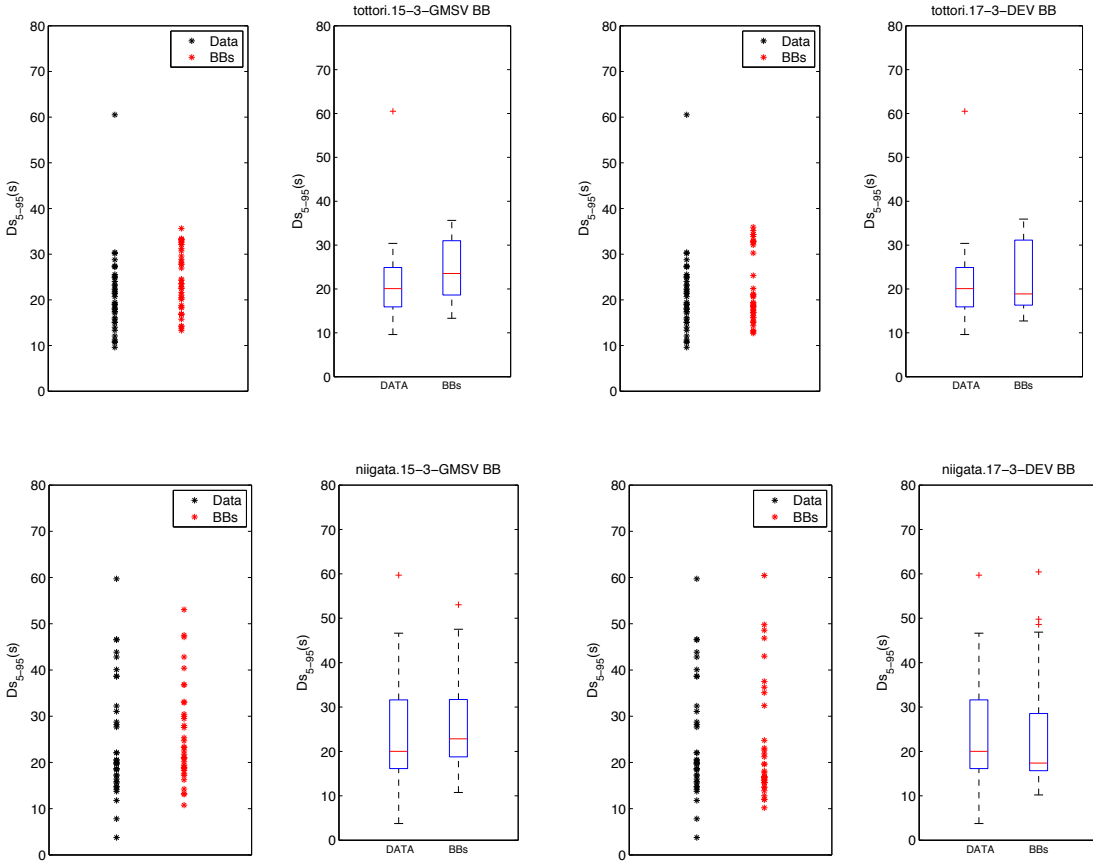
**Figure 11.** Changes in bias for the 50 realizations due to the new STF are shown for 8 SCEC validation events, with the earlier fit to NGA-West1 on top, and the fit to NGA-West2 at the bottom. Notice the improved fit for PSA in the scenarios. Thick line depicts the median, purple shading shows the 95% confidence interval, and light blue shading is for the standard deviation.



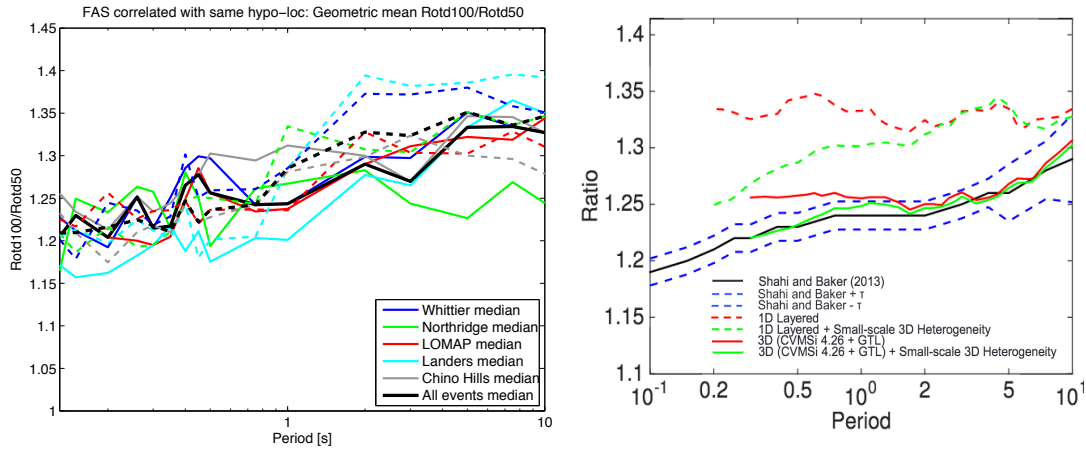
**Figure 11.** Illustration of the undesirable effects of using the (default) truncation of the synthetics alignment in calculating the GOF on the SCEC BBP. (top) Truncated data, (middle) synthetics (left) untruncated and (right) truncated and (bottom) Arias Intensity comparison of data and synthetics in the



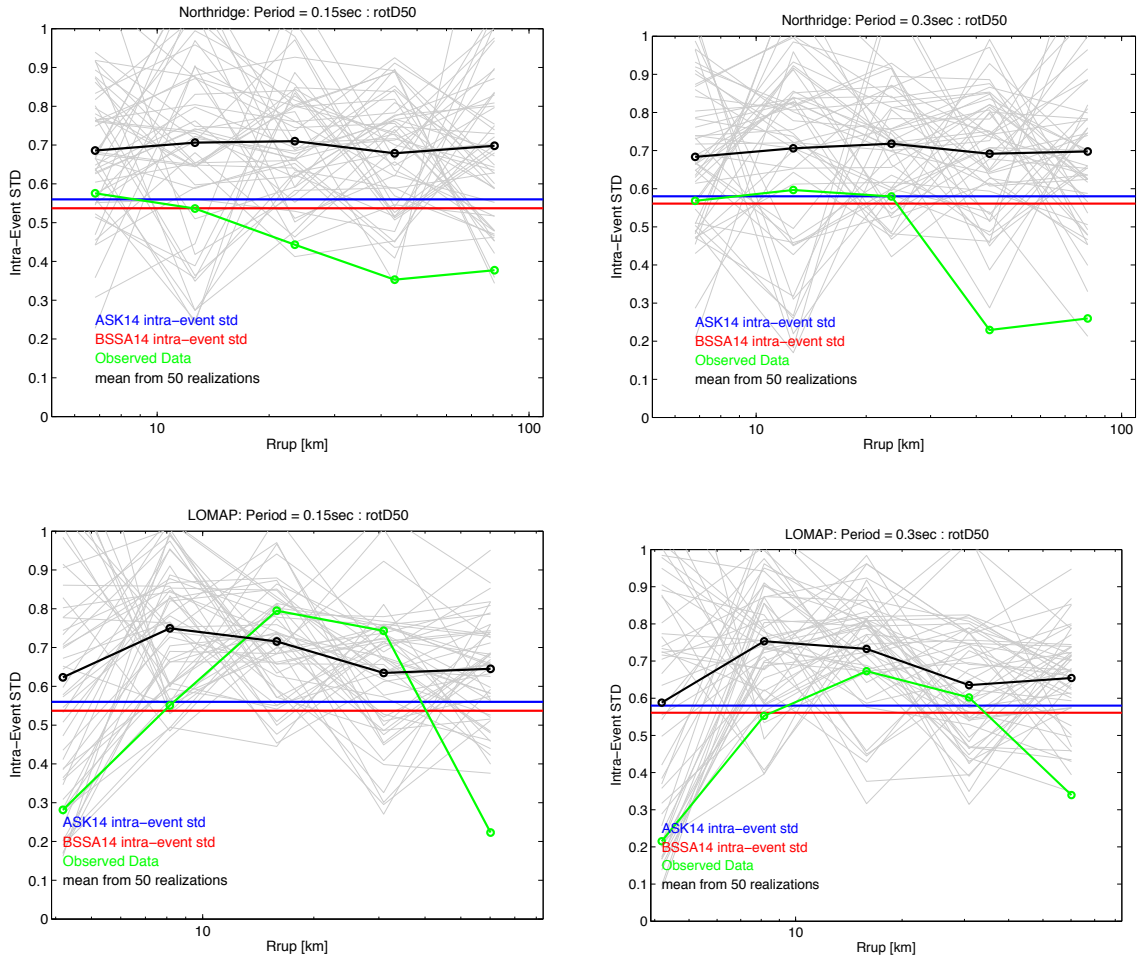




**Figure 12.** Comparison of  $D_{5-95}\%$  duration for 8 SCEC validation events (left two panels) for the old SDSU BBP module to (right two panels) the updated SDSU module.



**Figure 13.** Comparison of simulations to empirical models for the geometric mean ratio of SARotD100 to SARotD50. (left) SARotD100 to SARotD50 ratios for Whittier (blue), Northridge (green), Loma Prieta (red), Landers (cyan), and Chino Hills (black); solid lines depict ratios derived from the ~40 records used for the validation on the SCEC BBP, and dashed lines depict the average ratios from 2 realizations of the SDSU BBtoolbox synthetics. (right) SARotD100 to SARotD50 ratios for  $M_w 6.7$  buried blind thrust scenarios. GTL=GeoTechnical Layer. From Withers et al., 2016.



**Figure 14.** Intra-event standard deviations at periods of 0.15 s and 0.3 s for (top) 50 realizations of Northridge and (bottom) Loma Prieta (gray lines depict individual realizations, and black line the mean from the 50 realizations). Blue and red curves depict the values obtained from the ASK14 and BSSA14 NGA-West2 GMPEs, and the green curves show the result for the data recorded at the ~40 stations used for each event.